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PLASTIC DEFORMATION AND VISCOSITY OF ICE

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[Figures and tables referred to herein are appended. Figures in parentheses refer to the bibliography.]

Ice, which is a crystalline solid, is deformed plastically under the prolonged pressure of loads. Flow, which is characteristic of viscous materials, can be observed in it. In 1904, Hess (1) calculated the viscosity of ice according to the speed of the deformation (sag) of prisms. According to his calculation the viscosity of fresh-water ice at 0 degrees C = 10^{10} poise.

In 1906, Veynberg (2) determined the viscosity of fresh-water ice by the method of twisting a sample. The shape of the sample was approximately the same as in Hess' experiments -- 3-4 sq cm in cross section and about 10-30 cm long. Veynberg's different samples had viscosities from $2 \cdot 10^{12}$ - 10^{14}. Veynberg calculated that the viscosity of fresh-water ice near 0° C $\approx 10^{13}$ poise.

In recent years, in connection with the extensive use of ice crossings and of various kinds of constructions on ice foundations, the study of ice deformation under prolonged pressure has acquired great practical importance. It was necessary to determine the carrying capacity of ice by calculating its elastic and plastic properties. To determine this carrying capacity, it was necessary to know the properties of ordinary ice with average physical properties. This is the reason we set up experiments to study the plastic

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deformation not of individual small samples, but of a natural ice cover of large area. The method we adopted made it possible not only to determine the viscosity, but also to determine the carrying capacity of the ice directly. The method and the results of the experiment are described here.

The work was done on Lake Suzdal', at Ozerki, near Leningrad. The meterological station of UGMS (Main Administration of the Hydrometeorological Service) was the base.

Preparing the Ice

The ice for the experiment was formed on the surface of the water in ponds which were made in the ice-covered lake. These consisted of ice holes 3, 4, and 8 meters in diameter in the thick ice of the lake. The depth of the lake at the ice holes was 3 meters.

The ice was formed in clear, calm weather when the temperature of the air was between -5 and -10 degrees C.

Immediately before the ice formed, the water in the ice holes was carefully cleaned of fragments of ice and other foreign matter.

This was usually done in the evening, and a smooth, clear layer of ice 1-3 cm thick would form during the night. In those cases when thick ice (5-10 cm) was required, the ice was allowed to form over a period of several days. The irregularities in the thickness of ice were small and of no practical importance. Lake Suzdal' itself was the largest of our reservoirs. The ice on the lake was formed over the whole winter, and by the time of the experiment it was 40 cm thick.

Temperature of the Ice

Experiments on the ice were made at 0 degrees C. As the winter of 1944 was mild, this proved to be easy for us. When the temperature of the air was less then 0 degrees C, we covered the surface of the ice with a 2-or 3-cm-thick layer of dry snow. The thermal conductivity of snow is low, and the temperature of the ice covered with snow quickly reached 0 degrees C.

Experimental Method

Application of the load to the ice and the measurement of deformation were done with the following devices. Two unconnected beams were thrown across the pond. One of them could be walked on, and the weight-holder and the equipment for recording the deformation of the ice were placed on the other (Figure 1). The weight-holder [1] was a box to the bottom of which was fastened, through a flange, a rod [2] 40 cm long and 6 cm in diameter. The rod fitted loosely in the guide pipe set in the middle of the beam. The end of the rod had a hemispherical surface and hit against a circular base [3] 5 cm in diameter, which rested on the ice.

The structure of the instruments which recorded the deformation, "depressographs," is shown in Figure 2. The frame (ramka) [1] and the pulley rotating freely on its axis [2] were attached to the beam [3]. Two weights -- one [P_1] resting on the ice, and the other [P_2] serving as a counterweight -- were hung over the pulley on a line. The pointer [4] attached to the pulley, indicated the divisions on the scale [5].

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It was accurate to 0.01 cm. In the beginning seven instruments were set up along the length of the beam on both sides of the load. Since the load was central and the chart of the depression symmetrical along the radii, we later confined ourselves to observing the depressions on just one side of the load.

"Depressographs" of the Reynov design (4) were used to measure the deformation of ice 40 cm thick. A weight of 20-30 kilograms was attached to the end of a thin steel wire. The weight was lowered to the bottom of the lake (Figure 3). The other end of the wire with counterweight P_2 (2 kg) was hung over the pulley, the frame of which was attached to the instrument on the surface of the ice. The pointer attached to the wire recorded the deformation of the ice on the drum of the time mechanism. The measurement was accurate to 0.1 cm.

The 40-cm ice was produced by filling a 5-cubic meter-tank with water. The empty tank weighed 500 kg. A fire pump was used to fill it, and the process took three hours.

Results of Measurements

1. Elastic deformation

When short-time, small loads which do not cause cracks are applied, the ice deforms elastically. The elastic deformation is simultaneous with the application of the load. When the load is removed the ice returns to its former state and the deformation disappears. The readings of the instruments with the reverse effects of the loads upon the ice are given by way of example in Table 1. The thickness of the ice was 0.49 cm. The instruments were placed at different distances from the place of application of the load (along a radius).

It is also possible to observe reverse deformation with heavy loads, but in this case the observation period must be very short. When the experiment is prolonged, plastic deformation is added to the elastic and reverse reactions are not observed. The outline of the cross section of the depression is shown in Figure 4, in which the data of Table 1 are plotted on a graph. The distances from the load are plotted along the abscissa and the deformation in centimeters is plotted along the ordinate. It is apparent from Figure 4 that the hollow resulting from the depression is convex.

The change from convexity to concavity takes place in the immediate vicinity of the place of application of the load. We obtained this type of depression chart in every case with different thicknesses of ice and different loads.

As the load on the ice was increased the deformation increased fundamentally only in those parts of the ice which were within the limits of the original depression chart. The radius of the chart bore little relation to the size of the load applied and was primarily determined by the thickness of the ice. The close relation of the diameter D of the depression chart to the thickness h is apparent from Table 2.

2. Plastic deformation

When loads are applied over a long period of time, not only elastic, but plastic deformation as well, is observed. Plastic deformation increases steadily with time and may be many times the elastic deformation produced by the same load. The development of the depression chart (cross section)

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with time and with ice of different thicknesses is shown in Figures 5a, 6a, 7a, and 8a. The distance from the load (along the radius) is plotted along the abscissa, and the deformation in centimeters along the ordinate. Curves 1, 2, 3, and 4 correspond to the state of deformation at different times, reckoning from the beginning of the application of the load. The time periods are given below the figure. The loads at the time of deformation measurements are also presented there. In these experiments the hollow of the depression filled up with water to the average level of the water in the pond. The ice was perforated at some point and the water flowed out of it continuously as the deformation increased. Therefore only the initial load P caused the fundamental deformation of the ice, and the reaction of the water as a result of hydrostatic pressure was always eliminated. In these experiments the elastic deformation of the ice was always small in comparison with the total plastic deformation. It consisted of from 0-5% of the total deformation observed at the end of the experiment. The plastic deformation increases without interruption up to the time of the breakdown. In cases of plastic deformation, cracks are formed in the ice only at the moment of breakdown. As the drawings show, the nature of plastic deformation is uniform for ice of all thicknesses. The curves are convex, as in elastic deformation. The relation of deformation to time, calculated by the first instruments for ice of the same thicknesses, is shown in Figures 5b, 6b, 7b, and 8b. The deformation is shown on the abscissa and the time on the ordinate. The linear relationship shows that a definite constant speed exists for plastic deformation in ice of a given thickness with a given load. If we put the findings of the other instruments on these graphs -- that is, the deformation at points further removed from the place where the load is applied -- straight lines are also obtained, but with less incline. The rate of plastic deformation decreases with the distance from the point where the load is applied, and at a certain distance, R, it becomes equal to zero. In this way plastic deformation does not take place along the entire line of the elastic depression but is concentrated in a limited area. Accordingly, the value R -- the active radius of the load in plastic deformation -- is considerably less than in elastic deformation. In the case of ice 40 cm thick the active radius of elastic deformation is 25 meters. But plastic deformation is practically limited to 5 meters.

The rate of plastic deformation depends to a considerable extent upon the atmospheric temperature. In experiments with thin ice on cold days when a snow cover was not used, we found instances in which plastic deformation did not break the ice. In these cases a decrease in the rate of plastic deformation was noted in the course of time with a constant load. To maintain a constant deformation rate, it is necessary to increase the load gradually. Then the ice has a point of yield and behaves just as other crystalline substances considerably below the melting point.

3. Viscosity

The curve of the depression is shown in Figures 5a, 6a, 7a, and 8a. We shall designate the rate of plastic deformation of the layer directly adjoining the area of the radius r_0 by v_0; R is the active radius, that is the distance at which the plastic deformation and the rate of plastic deformation v are equal to zero. It is evident from the curves of Figures 5a, 6a, etc., that the radius R does not vary greatly with the increase of plastic deformation up to the time the ice breaks, since for a given thickness of the ice it can almost be regarded as constant.

For a stationary condition we can compare the viscous strength, $2\pi r h \eta \frac{dv}{dr}$ with the weight of the load P.

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After integrating and calculating the limited conditions, by which

$v = 0$ when $r = k$ and $v = v_0$ when $r = r_0$
we obtain the equation for viscosity:

$$\eta = \frac{P \ln \frac{K}{r}}{2\pi h v} \tag{1}$$

or

$$\eta = \frac{P \ln \frac{K}{r_0}}{2\pi h r v_0} \tag{1'}$$

This equation is derived from consideration only of breaking pressures. Actually a bend in the plate takes place due to normal pressures. From the point of view of Maxwell's theories the flow of plastic materials is a relaxation of pressures that exist in them. Therefore, those pressures to which a great deformation corresponds also show the greatest rate of plastic flow.

In our experiments, as the deformation calculations show, the bend was of great importance. This is especially true in the case of thin ice. By Maxwell's theory, we can determine the viscosity of ice by the following method as well.

The deformation from the bend of a circular plate, loaded in the center with the concentrated force P and fastened at a distance R from the centers, is

$$f_{bend} = \frac{3(1-\sigma^2)}{4\pi E h^2} P \left[R^2 - r^2 - 2r^2 \ln \frac{R}{r}\right], \tag{2}$$

where σ is Poisson's coefficient, r is the radius at the point on the curve under consideration, and E is the coefficient of elasticity (90,000 kg/sq cm). (8)

In accordance with Maxwell's theory, we can now replace f_{bend} with the rate of plastic deformation v, and $\frac{E}{3}$ with viscosity η. Then

$$\eta = \frac{9P}{16\pi 3v \cdot h^3} \left[R^2 - r^2 - 2r^2 \ln \frac{R}{r}\right] \tag{3}$$

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or, for the center of the plate

$$\eta = \frac{9R^2 P}{16\pi 3 v_0 h^3}. \qquad (3')$$

Equations (1) and (3) are needed for correction of the effect of the distributed load, arising from the difference in the densities of the ice and water, upon the ice. We shall consider this load evenly distributed over the entire surface of the ice having an area of πR_1^2, the ice being already submerged in the water. Beyond the limits of this area it will be equal to zero. Then to v in equations (1) and (3) it is necessary to add the rate

$$v' = -\frac{\Delta\delta g(R_1^2 - r^2)}{4\eta}, \qquad (4)$$

where $\Delta\delta$ is the difference in densities of the water and ice, and g is the acceleration from the force of gravity. Since the deformation curve is not very sharp R_1 is somewhat less than R and, as is evident from the curves in the drawings, it increases with the development of the plastic deformation.

V' is considerably less than the rates experimentally observed, and therefore we did not take it into account in the viscosity calculation.

It is evident from equations (1) and (3) that to determine viscosity it is sufficient to know the rate of plastic deformation (v_0) in the layer directly adjoining the place where the load is applied (r_0). We used the findings of the first instrument for maximum deformation, and we calculated v_0 from the curves in Figures 5b, 6b, etc. It should be noted that equations (1) and (3) may also be used. In those equations for each radius r on the curve there is a corresponding rate of plastic deformation v. The result of this calculation is invariable. In Table 3 are given the data from our various experiments and calculations of the viscosity of ice according to equations (1') and (3').

We see that viscosity, calculated according to equation (1'), is considerably less than when calculated by equation (3'). This was to be expected, since equation (1') is applicable for shear displacement, and in our experiments the essential part was played by the bend.

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In Veynberg's experiments, in which the viscosity of ice was determined by the angle-of-twist method, there was sheer displacement. According to his data, ice viscosity at 0 degrees C is 10^{13} poise. The results of our data, assembled in the following column, are near this value.

It should be noted that in the experiments of Hess as well as in ours, the bend played the leading part. Nevertheless, by mistake, Hess used only the shearing pressures in his calculations, and as a result he obtained much too low a value for viscosity -- 10^{10} poise.

Recalculation of viscosities from his data gives a considerable increase in viscosity and less divergence from the data of Veynberg. The difference in viscosities is also observed in other experiments. The difference between Veynberg's and ours, as can be seen from Table 3, is evidently to be explained by the difference in the conditions of the experiment and the growth of the ice. Viscosity is one of the characteristics of the mechanical properties of a substance very sensitive to structural changes. Therefore small variations in the freezing conditions of the ice -- its temperatures, etc. can result in a sharp difference in its viscosity. Allowing for this, we can conclude that the results of our experiments, which were carried out under field conditions and written up according to Maxwell's theory, give approximately the same viscosity value for fresh-water ice as other experiments of the laboratory type.

4. Bend Curve

The deformation at each separate point on the curve, just as the full curve, must be the total effect of deformation in bending and in breaking.

The deformation with a bend in a circular plate with a concentrated load in the center and with a firmly fastened edge is described by equation (2). According to this equation, the deformation curves are parabolas, starting from the place of application of the load and ending at the maximum radius R. The equation for deformation in breaking follows from equation (1), and for a given interval of time

$$f_{breaking} = \frac{P \cdot \ln \frac{R}{r}}{2\pi h \eta} t = C \ln \frac{R}{r}, \qquad (5)$$

where C is a constant.

According to this equation, the deformation speedily increases with decrease in the radius r, that is, with the approach to the place where the load is applied. The curves are convex instead of concave, as follows from equation (2).

The bend curves we obtained experimentally are well described by equation (5) and can not be represented by equation (2) at all. It follows from this, that deformations at the point of breakdown determine the form of deformation curves or the curve in the case of concentrated loads.

The deformation curve, according to equation (2), is to be expected only with large areas of distribution.

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5. Carrying Capacity

Under long-time loads the plastic deformation of ice increases with time, and when it reaches a certain value it causes fracture.

The value of this breakdown deformation is one and the same for a given thickness of ice. The relationship of the breakdown deformation to the thickness of the ice is given in Table 4.

With large loads the breakdown deformation values are quickly reached, and with small loads it goes slowly and may take a very long time.

The time required for plastic deformation to reach the fracturing point is determined by those pressures as a result of which the ice flows. The ice sustains the greatest breakdown pressures around the perimeter of the base on which the load is placed. In our experiments round supports with a radius r_0 served as bases. The breakdown pressures may be calculated by the equation

$$\tau = \frac{P}{\Pi h} = \frac{P}{2\pi r_0 h}, \qquad (6)$$

where Π is the perimeter of the support. It follows from our data that the time of onset of the breakdown is shortened considerably with increase of the breakdown pressures. When τ = 0.2 kg/sq cm the ice breaks at the end of 8 days, and when τ = 1.35 kg/cm [sic] it breaks after 13 minutes.

The breakdown pressure τ = 0.2 kg/sq cm is the lowest in our experiments at which breakdown resulted from plastic deformation. We recommend not exceeding this value in cases when the burden remains on the ice cover for a long time. This means, for example, that a 3-ton automobile should not stand for a long time on ice even 30 to 40 cm thick, or a person of medium weight on 5- to 6-cm. ice, etc.

But ice of these thicknesses is fully passable for automobiles and persons, respectively.

The time which a load stands on ice may also be limited by the extent of the bending movements. We shall not go into this due to lack of space.

We were assisted in this work by our scientific colleagues of GUMS Ivanov, Kolokol'tsov, and Rozhanskaya. We express our thanks to them here.

RESUME

1. A method was described of studying the plastic deformation of floating natural ice.

2. Charts are given of elastic and plastic ice deformation.

3. It was shown that the rate of plastic deformation is constant with a constant prolonged load.

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4. A method of measuring the viscosity of floating natural ice was developed.

5. The viscosity of ice at 0 degrees C was determined.

6. It was proved that plastic deformation even with small loads eventually leads to breakdown of the ice, if its temperature ≅ 0 degrees C.

Dangerous and safe values of breakdown pressures for long-time burdens on ice are determined.

BIBLIOGRAPHY

1. H. Hess, Ann. d. Phys. 8, 405, 1902
2. V. Veynberg, Ice, GTTL, 1940
3. K. Koch, Weid. Ann., 25, 438, 1885
4. N. M. Reynov, ZhTPh, XIII, 661, 1943
5. M. Segal, Phys. ZS, 4, 493, 1903
6. G. Tammann, ZS f. Phys. Chem., 28, 17, 1899
7. A. F. Ioffe, The Physics of Crystals, GIZ, 1929
8. I. V. Gekkeler, The Statics of an Elastic Body, ONTI, 1934

[Figures and Tables follow]

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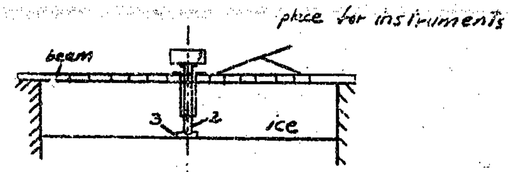

Figure 1

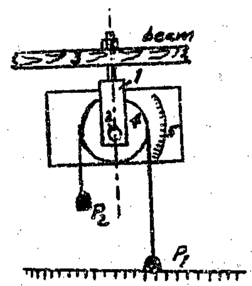

Figure 2

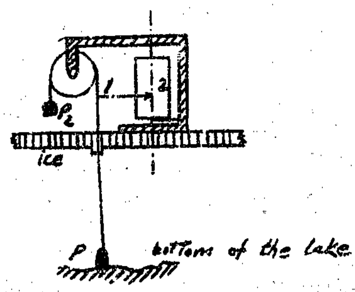

Figure 3

Table 1

Readings of the Instruments (Cm)	Distance from Application of Load (Cm) 15	45	105	135
Before application of the load	0	0	0	0
With a load of 200 gm	0.7	0.4	0.1	0
After removal of the load	0.5	0	0	0
With a load of 200 gm	0.7	0.3	0	0
With a load of 1200 gm	2.7	1	0.2	0
After removal of the load	0.6	0	0	0

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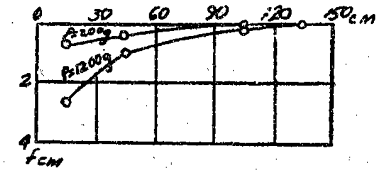

Figure 4

Table 2

h(Cm)	D(M)
1	2 - 2.5
2	4 - 4
5	6.5 - 7.5
10	10 - 11

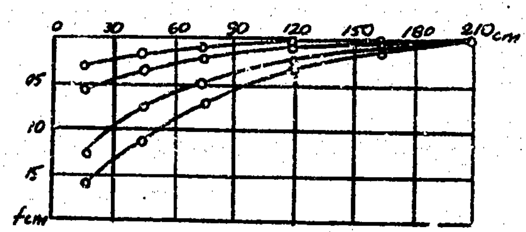

Figure 5a

P = 32 kg, h = 1.5; 1 - t = 1 min, 2 - 3 min,
3 - 6 min, 4 - 8 min

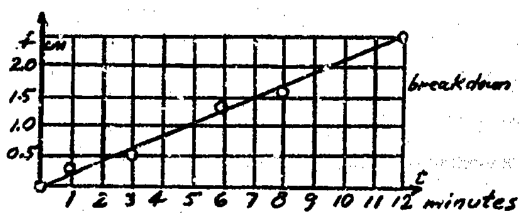

Figure 5b

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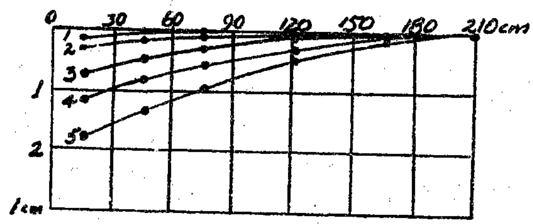

Figure 6a

P = 10.2 kg, h = 1 cm; 1 - t = 2 min, 2 - 10 min, 3 - 3.5 min, 4 - 65 min, 5 - 95 min

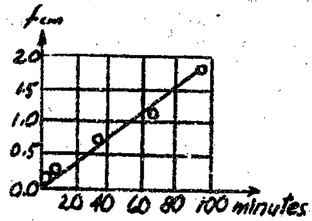

Figure 6b

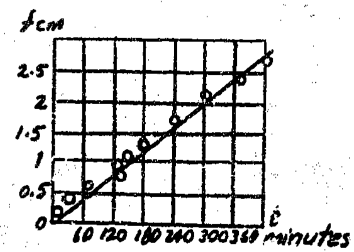

Figure 7b

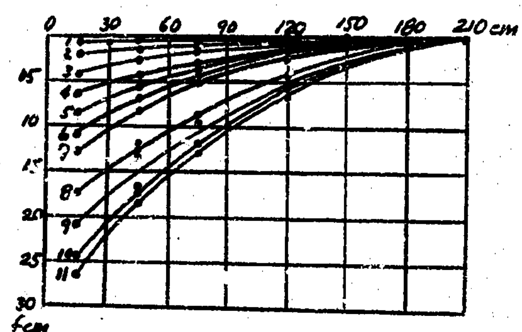

Figure 7a

P = 7.2; h = 1 cm; 1 - t = 1 min; 2 - 12 min; 3 - 35 min; 4 - 72 min; 5 - 127 min; 6 - 150 min; 7 - 183 min; 8 - 240 min; 9 - 305 min; 10 - 365 min; 11 - 425 min

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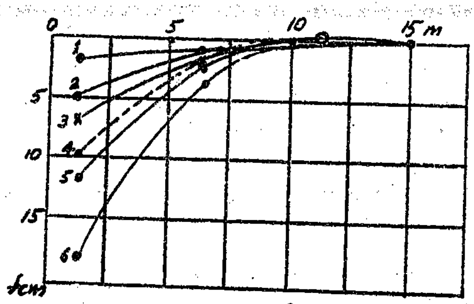

Figure 8a

$P = 6 \cdot 10^3$ kg; h = 40 cm; 1 - t = 1 day, 2 - 2 days; 3 - 4 days; 4 - 6 days; 5 - 7 days; 6 - 8 days

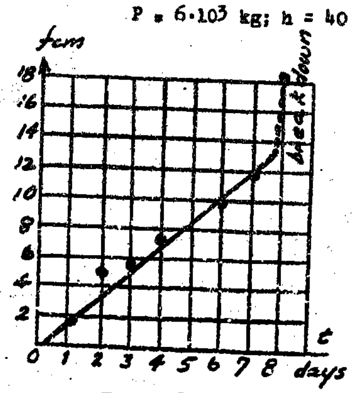

Figure 8b

Table 4

h Cm	Plastic Deformation in Cm
1	2 - 3
5	5
40	14

Table 3

No p/p	h Cm	P Kg	r_0 Cm	R Cm	v_0 Cm/sec	Poise by Formula (1')	Poise by Formula (3')
1	1	7.2	2.5	220	$1.17 \cdot 10^{-4}$	$4.4 \cdot 10^{10}$	$22 \cdot 10^{14}$
2	1	7.2	2.5	220	$2.25 \cdot 10^{-4}$	$2.3 \cdot 10^{10}$	$9.2 \cdot 10^{13}$
3	1	10.2	7.5	220	$2.8 \cdot 10^{-4}$	$2 \cdot 10^{10}$	10^{14}
4	1.5	32	2.5	220	3.[illegible] $\cdot 10^{-3}$	$5.5 \cdot 10^{9}$	$1.1 \cdot 10^{13}$
5	2	17.2	2.5	90	$1.28 \cdot 10^{-4}$	$3.8 \cdot 10^{10}$	$8.1 \cdot 10^{12}$
6	2.8	17.2	2.5	150	$4.16 \cdot 10^{-4}$	10^{10}	$2.8 \cdot 10^{12}$
7	5	100	2.5	400	$5 \cdot 10^{-4}$	$3.2 \cdot 10^{10}$	$1.07 \cdot 10^{13}$
8	40	$6 \cdot 10^3$	$1.5 \cdot 10^2$	10^3	$2 \cdot 10^{-5}$	$2 \cdot 10^{12}$	$7.85 \cdot 10^{13}$

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